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A Method to Assess Assembly Complexity of Industrial Products in Early Design Phase

BUGRA ALKAN, DANIEL VERA, BILAL AHMAD, (Member, IEEE), AND ROBERT HARRISON
Warwick Manufacturing Group, University of Warwick, Coventry CV4 7AL, U.K.

Corresponding author: Bugra Alkan (b.alkan@warwick.ac.uk)

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ABSTRACT Complexity is one of the factors, inducing high cost, operational issues, and increased lead time for product realization and continues to pose challenges to manufacturing systems. One solution to reduce the negative impacts of complexity is its assessment, which can help designers to compare and rationalize various designs that meet the functional requirements. In this paper, a systemic approach is proposed to assess complexity of a product's assembly. The approach is based on Hückel's molecular orbital theory and defines complexity as a combination of both the complexity of product entities and their topological connections. In this model, the complexity of product entities (i.e., components and liaisons) is defined as the degree to which the entity comprises structural characteristics that lead to challenges during handling or fitting operations. The characterization of entity complexities is carried out based on the widely used DFA principles. Moreover, the proposed approach is tested on two case studies from electronics industry for its validity. The results showed that the approach can be used at initial design stages to improve both the quality and assemblability of products by reducing their complexity and accompanying risks.

INDEX TERMS Product design, assembly, design optimisation, complexity analysis.

I. INTRODUCTION

Assembly processes significantly affect products' final quality and cost [33]. According to Choi *et al.* [11], assembly related activities credit for more than 50% of the total production time and 20%-40% of the total production cost. These findings show that assembly processes form a significant proportion of the production cost and time, which implies that any improvement in assembly has direct implications on the turnover [23]. Nowadays, products are becoming more complex, however, they still need to maintain their quality and reduced lead time. One strategy that industries adopt to overcome this challenge is to commission highly flexible assembly systems that encompass sub-systems of different functionalities [2]. While ensuring that the system is able to satisfy the rapidly changing functional requirements, complexity increases as more components and more interfaces are introduced to the system at both hardware and software levels [9]. This leads to not only huge inefficiencies in system design and re-configuration stages but also bottlenecks in shop floor decision-making under disruptive events such as machine failures [10]. As complexity increases, assembly systems become less responsive to change and harder to manage and control [5]. Thus, evaluating the root causes of complexity at early design stages becomes an imperative implementation to design and build systems that are diagnosable, predictable and productive. These traits translate directly into reduced costs due to ease of maintenance, foresight and efficient use of resources.

One of the main complexity drivers, product variety, necessitates a higher degree of flexibility for handling components due to the variations in the technical and functional aspects of products such as: shape, size, and configuration. This results in higher uncertainty and costs due to the new or modified equipment that must accommodate the product variety and floor space requirements. This, in turn, reduces the efficiency of the facility and results in line balancing problems. Moreover, almost one-third of a manufacturing enterprise's human workforce is employed in assembly and related activities [27]. The uncertainty created by product variety is attributed to the complexity of tasks that operators need to carry out which, if not designed correctly, can reach the cognitive and physical limits of humans [3]. Therefore, designing products by taking ease of assembly into consideration can help to reduce assembly time/difficulty and defect rates, especially in high variety assembly systems [26].

In this paper, a systemic approach has been proposed to assess assembly complexity of manufacturing products in a quantitative and repeatable manner. The approach defines the complexity of product's assembly operations as a combination of the complexity of product's individual components, complexity of assembly liaisons, and complexity of the product's topological structure. Due to its comprehensive complexity definition, the approach allows designers to better track the possible root causes of assembly complexity arising due to the product's inherent structure than the approaches proposed in the literature. Also, the approach supports assembly operations which can be done either manually or by an automatic assembly system.

II. LITERATURE REVIEW

Complexity is a major research area in various scientific disciplines including; physics, biology, and the social sciences. Numerous studies have been carried out in an attempt to define the nature of complexity and characterise it, however, a universal, precise and widely accepted terminology has not been achieved yet [4]. Various discussions about complexity are focused on the basic notion of difficulty [19]. There is also an emphasis on the subjective nature of complexity being dependent on the system being considered and the view of the human spectator [14].

Complexity has a strong positive correlation with difficulty; as the system becomes more complex, the more difficult it is to develop, maintain, and use, the more complicated a task, the costly and error prone it is [24]. In addition to the requirements of a large amount of time for designing and integrating components, complex systems have intricate topologies or patterns which may result in reduced productivity and increased failure rates during their design and development stages [31]. One way of preventing mistakes, in the context of system development, is to assess and reduce complexity without compromising functional requirements and performance targets as much as possible [29]. According to McCabe [20], assessing the complexity of a design is vital with regard to predicting the cost and time essential to realise the design. Assessment of complexity also makes it visible whether the current state of the design is comprehensible for humans [31].

In the literature, complexity of an assembly is mainly studied either by analysis of the product to be assembled or the process sequence for the assembly [1]. The models solely based on the physical attributes of the parts are primarily influenced by approaches, by which products are designed with ease of assembly in mind, such as; Design for Assembly and Manufacture (DFMA) [6], the Lucas Method [8] and the Hitachi Assembly Evaluation Method (AEM) [21]. Although these approaches have varied methodologies, the outcomes are similar *i.e.* reduction in part numbers, optimising part handling and insertion attributes, and penalising inefficient designs, *etc.* [1]. These approaches are not intended to examine assembly complexity, instead they attempt to enhance the product design according to the empirically verified data.

Based on an empirical study focusing on assembly deficiencies of semiconductor assembly, Hinckley [15] found that the assembly defect rate per assembled unit is positively linked to the total assembly time. His assembly complexity factor based on the Westinghouse DFA worksheet suggests a theoretical time required to assemble a product. However, this approach requires actual production data (*i.e.* the incidence of defects that occurred in the plant) and does not consider the assembly design factors which are required to evaluate the defect rates for a particular assembly station. Shibata *et al.* [28] extended Hinckley's methodology and proposed an upgraded model by combining process and design based complexity factors. In Shibata's methodology, the process-based complexity factor is a function of the number of job elements in the workstation, an arbitrary threshold assembly time and time spent on individual job elements which is calculated based on the method of Sony Standard Time (SST). Design complexity factor, on the other hand, is defined as a ratio between a subjective calibration coefficient and ease of assembly results of corresponding workstations, which is calculated through the Design for assembly/disassembly Cost-effectiveness (DAC). Su *et al.* [33] proposed a modified Shibata's methodology which is valid for a copier assembly to predict human induced assembly errors. Although these models provide a robust assessment of assembly complexity, the design complexity criteria and time estimation methodologies used in these prediction models are designed for individual assembly types.

ElMaraghy and Urbanic [13] developed an '*operational complexity index*', which is designed as a function of the quantity and diversity of both product and process elements and a relative complexity coefficient which is introduced to capture their information content. The proposed approach considers physical (*i.e.* temperature, cleanliness, envelope, strength and dexterity) and cognitive elements (*i.e.* procedures, in-process relationships and performance issues) to calculate the relative effort of each manufacturing task. Samy and ElMaraghy [27] extended the initial approach by adding DFA criteria to evaluate the assembly complexity of individual product parts. Complexity indices are combined to acquire an overall measure for total product assembly complexity, including quantity and diversity of the parts. Richardson *et al.* [25] proposed a practical model to predict the difficulty of assembly of an object solely based on its physical attributes. It considers the number of components, symmetrical planes, fastenings, fastening points and novel assembly to formulate an equation which was refined using experiments in which the above-mentioned variables affect the thinking time during assembly. However, the approach is based on the data collected for a specific type of assembly, therefore, requires further work to produce the definitive model.

In summary, the approaches found in the literature on products' assembly complexity either require real production data or are designed for a specific application. Therefore, a methodology allowing designers/engineers to systematically analyse the impacts of the product's complexity on its assemblability, while highlighting the potential root causes of the design complexity, is necessary, especially for early design-stages.

III. MODELLING PRODUCT's ASSEMBLY COMPLEXITY

This section presents a systemic methodology which can be used to support early design phases of assembly products, where complexity of product's assembly, and critical design parameters can be identified, verified and optimised.

A. HUCKEL's MOLECULAR ORBITAL THEORY

The approach presented in this paper is based on Huckel's molecular orbital theory [16] which aims to analyse configuration energy of π electrons in conjugated hydrocarbon systems. In Huckel's model, the configuration energy of atomic orbitals is expressed as a function of *i*) self-energy of the individual atoms in isolation, *ii*) interaction energy between interconnecting atoms, and *iii*) the effects of the molecular system topology. In here, the configuration energy outlines the distinctive ability of the interacting system to respond to its surroundings and higher values show an increasing effort required to develop/manage the system [29]. The Huckel's molecular orbital theory is chiefly introduced to engineering domain by [30], to analyse complexity of cyber-physical systems. In their research, they have argued that any engineering system can be represented by a number of components that are connected to each other in varying ways, where each component can be thought of as an atom and the interfaces between them as inter-atomic interactions (*i.e.* chemical bonds). In this analogy, complexity C associated with the system's inherent structure is defined as below.

$$C = C_1 + C_2 C_3 \tag{1}$$

In here, the first term C_1 symbolises the sum of complexities of individual system components, which are designated by α_i:

$$C_1 = \sum_{i=1}^{N} \alpha_i \tag{2}$$

where N is number of components. This term indicates the technical/ergonomical difficulty/effort associated with the development and management of the component in an isolated condition, and does not require system's architectural information.

The second term C_2 represents the sum of complexities of each pair-wise interaction, which is defined as β_{ij},

$$C_2 = \sum_{i=1}^{N} \sum_{j=1}^{N} \beta_{ij} A_{ij} \tag{3}$$

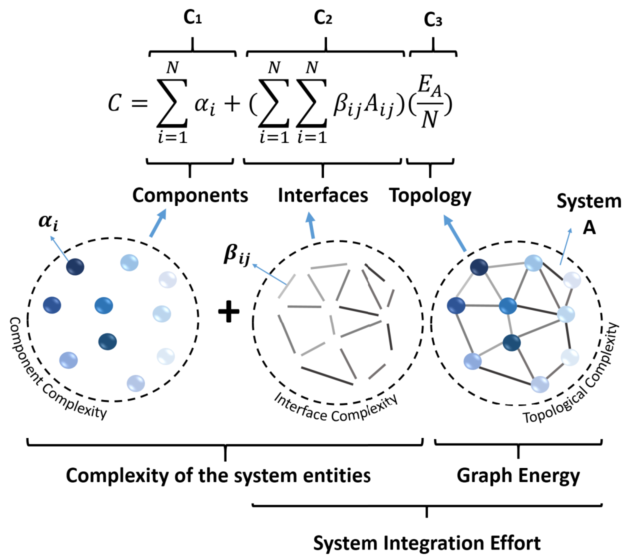

FIGURE 1. **Elements of the overall complexity metric.**

where A_{ij} defines the binary adjacency matrix representing the connectivity structure of the system:

$$A_{ij} = \begin{cases} 1 & \text{if there is a connection between i and j} \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

Similarly, the term C_2 indicates the technical/ergonomical difficulty/effort associated with the development and management of each pair-wise interaction, and requires knowledge about the inherent nature of each interface as well as the overall system architecture.

The last term, C_3 is a global measure that encapsulates the inherent arrangement of connections and is calculated by the *graph energy* E_A (see [22]).

$$C_3 = \frac{E_A}{N} \tag{5}$$

Notice that, the term C_3 requires knowledge of the complete system architecture, and in this sense, contrary to the previous terms, signifies a global effect whose influence could be perceived during the system integration phase [29]. Therefore, the term $C_2 C_3$ can be referred as a general indicator of system integration effort. In summary, the analogy defines structural complexity of a system (A) in a functional form as follows:

$$C = \sum_{i=1}^{N} \alpha_i + (\sum_{i=1}^{N} \sum_{j=1}^{N} \beta_{ij} A_{ij})(\frac{E_A}{N}) \tag{6}$$

Figure 1 shows the constituent elements of the complexity metric.

B. ADAPTATION OF HUCKEL's THEOREM TO INDUSTRIAL PRODUCT ASSEMBLY

The structure of an assembly product is composed of a set of components and liaisons. Components include:

i) essential components, *ii*) quasi-components and *iii*) virtual components. Essential components can be individual parts or sub-assemblies that behave as a single unit. Quasi-components are used to connect two essential components. These components include threaded (*e.g.* screws, bolts, nuts, *etc.*) and non-threaded mechanical fasteners (*e.g.* snap fits, rivets, *etc.*). Virtual components, on the other hand, are used to represent non-mechanical fasteners, such as: soldered/welded and glued joints. Liaisons are the interactions that physically attach two components to restraint the motion between them [18]. In general, an assembly task is performed to set up these interactions in sequential order to assemble the final product.

The structure of an assembly product can be represented in multiple ways. One of these, known as liaison diagram, graphically visualises the complete product structure using a non-directed graph. In this representation, components are expressed by nodes, and liaisons are defined by edges. Based on the selected level of detail, liaison diagrams can be illustrated in three different forms: *i*) extended form, *ii*) reduced form and *iii*) minimal form [34].

Figure 2 shows an assembly product with five components of which, A and B are connected by snap-fitting, B and C are connected with a screw E, and C and A are connected by a weld joint D. The extended liaison diagram includes all components, while the reduced form of the liaison diagram representing the product structure more briefly by hiding virtual components and using dashed lines for quasi-components. The minimal form represents the product structure in a more compact way by only including essential components and the direct connections between them in the diagram. This form is the simplest way while keeping the information concerning the essential components visible.

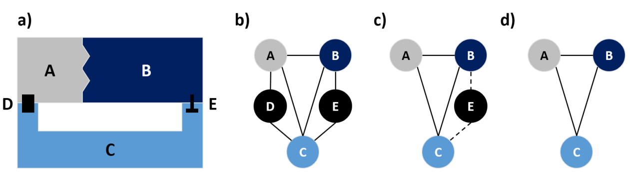

FIGURE 2. **Representation of assembly products, *a*) product structure, *b*) extended liaison diagram *c*) reduced liaison diagram *d*) minimal liaison diagram (adapted from [34]).**

The assembly product structure can also be represented by the assembly structure matrix (ASM) [34]. Unlike design structure matrix (DSM) which visualises dependencies between system components (*e.g.* structural connections, information exchange, material and energy transfers, *etc.*), ASM approach only depicts liaison connections (*i.e.* how components are joined together). The ASM is a N-by-N symmetrical matrix, where each element of the matrix designates the existence of an assembly liaison between two components:

$$[ASM]_{ij} = \begin{cases} 1 & \text{liaison exists between } i \text{ and } j \\ 0 & \text{otherwise} \end{cases} \tag{7}$$

Diagonal elements of ASM are always zero. As an example, the ASM for the extended form of the above-mentioned example is given below.

$$[ASM] = \begin{vmatrix} 0 & 1 & 1 & 1 & 0 \\ 1 & 0 & 1 & 0 & 1 \\ 1 & 1 & 0 & 1 & 1 \\ 1 & 0 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 \end{vmatrix} \tag{8}$$

In this research, an assembly product is thought as a stand-alone system consisting of a number of components handled and inserted by either human operators or assembly machines in sequential order to form the product. In here, it is hypothesized that the assemblability of the product is linked to its structural complexity, therefore, any reduction in the complexity without compromising product's functionality will enhance the quality of the assembly and reduce associated costs. By adapting the Huckel's approach presented in the previous section, the assembly complexity of manufacturing products C^p is defined as follows:

$$C^p = C_1^p + C_2^p C_3^p \tag{9}$$

where C_1^p, C_2^p, C_3^p represent component, liaison and topological complexity of the product, respectively. This section discusses the rationale behind the estimation of the various elements of the product complexity metric.

1) COMPLEXITY OF PRODUCT COMPONENTS, C_1^p

Components complexity C_1 represents the sum of complexities of individual system components. In case of an assembly product, this term is labelled as C_1^p and calculated as follows:

$$C_1^p = \sum_{i=1}^{N_p} \alpha_i^p \tag{10}$$

where α_i^p represents the complexity of the product component i, and N_p defines the total number of components (excluding virtual components) forming the product. In this context, complexity of a product component is defined as the ergonomical/technical difficulty to interact with the component, and measured based on the degree to which the component has physical characteristics that result in difficulties or problems during its handling during manual and automatic assembly operations. In this research, handling difficulty of assembly components is estimated using a methodology derived from the Lucas Method [8] (Table 1). The Lucas Method is a point scale product design analysis method which provides a relative measure of difficulty of both manufacturing and assembly operations. In the approach, issues regarding the handling of assembly components are evaluated by the *handling index*. This index indicates the average handling difficulty of components and it is calculated based on the physical factors of size, weight, handling difficulties and orientation. In this study, the normalised handling index

TABLE 1. **Complexity of part handling attributes f_h (adapted from [8]).**

Attribute	Description	f_h
A - Size and weight (One of the following)	Very small - requires handling aids	1.5
	Easy - requires one hand only	1
	Large and/or heavy - requires more than one hand or aid	1.5
	Large and/or heavy- requires hoist or more than one person	2
B - Handling difficulty (All that apply)	Delicate	0.4
	Flexible	0.6
	Sticky	0.5
	Tangible	0.8
	Severely nest	0.7
	Sharp/abrasive	0.3
	Untouchable	0.5
	Gripping problem/slippery	0.2
	Automatic handling - no difficulty	0
C - Alpha Symmetry (One of the following)	Symmetrical - no orientation required	0
	Easy to orient - end to end	0.1
	Difficult to orient - end to end	0.5
D - Beta Symmetry (One of the following)	Rotational orientation is not required	0
	Easy to orient - end to end	0.2
	Difficult to orient - end to end	0.4

is used to define the complexity of product components α_i^p:

$$\alpha_i^p = \frac{f_h^A + \sum_1^{N_B} f_h^B + f_h^C + f_h^D}{\alpha_{max}^p} \tag{11}$$

where α_i^p is the complexity of i^{th} component, N_B is the number of applicable handling difficulties, and α_{max}^p is the theoretical maximum value for the handling index (6.9). A high value of α_i^p indicates an increased handling difficulty for the corresponding component. Since component complexity C_1^p is a cumulative score, eliminating non-essential components and designing for ease of handling will reduce product's cumulative component complexity.

2) COMPLEXITY OF ASSEMBLY LIAISONS, C_2^p

The complexity of liaisons C_2^p is the sum of the complexities of pair-wise connections that exist in the product structure. In this study, we only consider connections between essential components as liaisons. Therefore, the calculation of C_2^p is carried out by only considering the minimal form of the product's ASM. By adapting the presented complexity modelling framework, the liaison complexity can be defined as follows:

$$C_2^p = \sum_{i=1}^{N_p^e} \sum_{j=1}^{N_p^e} \beta_{ij}^p ASM_{ij}^{minimal} \tag{12}$$

$$[ASM]_{ij} = \begin{cases} 1 & \text{if there is a connection between } i \text{ and } j \\ 0 & \text{otherwise} \end{cases} \tag{13}$$

where N_p^e is the number of essential components. Complexity in achieving a liaison between essential components i and j (β_{ij}^p) can be expressed by the relationships between the linked components and the nature of the connection. In this study, we adapted the normalised *fitting index* from the Lucas Method to assess individual β_{ij}^p values. The *fitting index* predicts the difficulty of an assembly fitting by penalising the physical attributes that affect the fitting difficulty. These attributes include: the direction of the fitting, insertion type, visibility, *etc*., and is given in Table 2. complexity of establishing a liaison is calculated as follows:

$$\beta_{ij}^p = \frac{f_f^E + f_f^F + f_f^G + f_f^H + f_f^I + f_f^J + f_f^K}{\beta_{max}^p} \tag{14}$$

where β_{max}^p is the theoretical maximum value for the fitting index (12.4). Note that, high β_{ij}^p scores indicate an increase in difficulty/effort to achieve the corresponding liaison, which may be eliminated by reducing part insertion difficulties (*e.g.* use of self-secured connections, designing parts with self alignment, increasing visibility, *etc*.).

3) COMPLEXITY OF THE PRODUCT's TOPOLOGY, C_3^p

The architectural pattern of a product results in the topological complexity associated with the interactions between components and relies on the combinatorial nature of the system's interconnectivity [17]. By following the definition proposed by [29], topological complexity is expressed as the matrix or graph energy E (see [22]), which is designated by the sum of singular values σ_i of the minimal assembly structure matrix $E_{ASM^{minimal}}$ of the product under consideration.

$$C_3^p = \frac{E_{ASM^{minimal}}}{N_p^e} \tag{15}$$

$$E_{ASM^{minimal}} = \sum_{i=1}^{N_p^e} \sigma_i \tag{16}$$

This metric outlines the nominal effective dimension entrenched within the connectivity pattern [29]. According to Sinha [29], topological complexity increases as the system's structure shifts from centralised architectures to more distributed architectures. Furthermore, topological complexity is divided into three regions: $C_3 < 1$ hypoenergetic (centralised architecture), $1 \leq C_3 < 2$ transitional

TABLE 2. Complexity of part fitting attributes f_f (adapted from [8]).

Attribute	Description	f_f	
		Manual	Auto
E - Part placing	Self-holding	1	1
(One of the following)	Holding down required	2	1.2
F - Part fastening	Self-securing	1.3	1.1
(One of the following)	Screwing	4	1
	Riveting	4	1.3
	Bending	4	1.6
	Mechanical deformation	4	1
	Soldering or welding	6	1.6
	Adhesive	5	1.2
G - Direction	Straight line from above	0	0
(One of the following)	Straight line not from above	0.1	0.2
	Not straight line and/or bending is required	1.6	1.2
H - Insertion	Single	0	0
(One of the following)	Multiple	0.7	1.2
	Simultaneous multiple insertions	1.2	1.2
I - Restricted vision	Visible	0	0
(One of the following)	Not visible	1	0
J - Difficult to align	No	0	0
(One of the following)	Yes	0.7	0.8
K - Resistance to insertion	No	0	0
(One of the following)	Yes	0.6	0.8

(hierarchical/layered architecture), and $C_3 \geq 2$ hyperenergetic (distributed architecture) [29]. In a practical manner, topological complexity indicates the '*intricateness*' of structural dependency among assembly components [32]. Topological complexity C_3^p allows us to differentiate the product structures with similar component and liaison complexities, and to better predict the integration effort.

IV. INDUSTRIAL CASE STUDIES

The combination of the above-mentioned complexity elements allows us to comprehend how the structural characteristics of a product impact the complexity of its assembly process. This section presents the demonstration of the proposed metric on real engineering products.

A. PRINTED CIRCUIT BOARD (PCB) PRESSURE RECORDER DEVICE

The case presented in this section is of the manual assembly of a pressure recorder device. The example is taken from the DFA handbook [7]. Figure 3 shows the original design of the pressure recorder assembly and its liaison diagram. The assembly consists of six essential and eleven quasi-components, and eight liaisons. The analysis results of component and liaison complexities are shown in Table 3 and Table 4, respectively. Complexity of the product's topology is recorded as 1.396 indicating a hierarchical architecture. According to the results, the overall complexity of the product's assembly C^p is calculated as 7.776.

As a next step, the original pressure recorder is re-designed based on the design for serviceability (DFS) principles (see [12]), as it is shown in Figure 4. In the improved design, the component number eleven of the initial design is completely removed, as it is tightly coupled with the remaining structure, and the component structure is re-arranged to accommodate the fewest possible number of quasi-components. Tables 5 and 6 show the component and liaison complexities of the improved pressure recorder design, respectively. The topological complexity of the new design is noted as 1. These values indicate that the improved design has 63.2% reduction in the overall product complexity when compared to the original design (from 7.776 to 2.864).

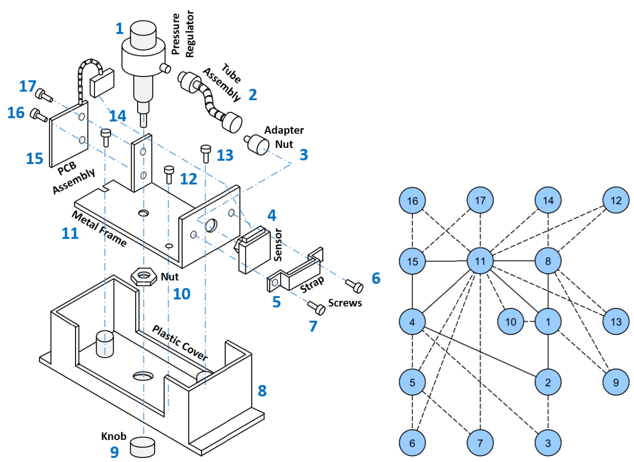

FIGURE 3. Initial design of the pressure recorder device and its liaison diagram $C^p = 7.776$ $C_3^p = 1.210$. (Product schematic is taken from [7].)

Figure 5 shows the graphical comparison between complexity scores of the analysed pressure recorder designs. The presented complexity model indicates that the C^p score of initial design is 63.2% higher than that of the improved design. Since, the improved design uses only three quasi-components and a snap-fit, the liaison complexity is reduced by 60.3%. Moreover, the contribution of component complexities has

TABLE 3. Calculation of component complexities - original pressure recorder design.

	Component																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
f_h^A	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
$\sum f_h^B$	0	0.6	0	0	0	0	0	0	0	0	0	0	0	0	0.6	0	0
f_h^C	0.1	0	0.1	0.1	0.1	0.1	0.1	0.5	0	0	0.5	0.1	0.1	0.1	0.1	0.1	0.1
f_h^D	0.2	0	0	0.2	0.2	0	0	0.2	0	0	0.4	0	0	0	0.2	0	0
α_i^P	0.19	0.23	0.16	0.19	0.19	0.16	0.16	0.25	0.14	0.14	0.28	0.16	0.16	0.16	0.28	0.16	0.16
C_1^p																	**3.159**

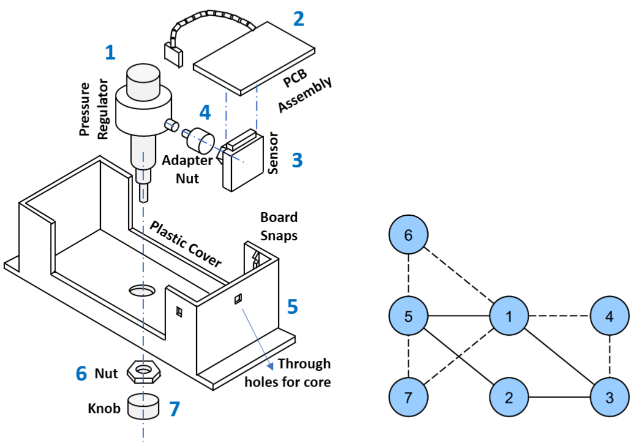

FIGURE 4. Redesign of the pressure recorder device and its liaison diagram $C^P = 2.864$ $C_3^P = 1.000$. (Product schematic is taken from [7].)

TABLE 4. Calculation of liaison complexities - original pressure recorder design.

	Liaison							
	1-2	1-8	1-11	2-4	4-11	4-15	8-11	11-15
f_f^E	2	1	1	2	2	2	2	1
f_f^F	1.3	4	4	4	4	1.3	4	4
f_f^G	0.1	0	0	0.1	0.1	0.1	0	0.1
f_f^H	0	0	0	0	0.7	0	1.2	0.7
f_f^I	0	1	1	0	0	0	0	0
f_f^J	0	0	0	0.7	0	0.7	0	0
f_f^K	0	0	0	0	0.6	0	0.6	0
β_{ij}^P	0.27	0.48	0.48	0.55	0.60	0.33	0.63	0.47
C_2^p								**3.815**

been reduced by 57.3% in the improved version through the elimination of non-essential fasteners. Additionally, the improved version also indicates a 17.4% reduction in the topological complexity score. As expected, the changes to the design have enhanced the handling and fitting attributes of the components, while increasing simplicity in the product's assembly topology. This reduces the excess complexity which is the difference between actual product complexity and the essential complexity that is the non-measurable basic level of complexity required by the product to satisfy its

TABLE 5. Calculation of component complexities - improved pressure recorder design.

	Component						
	1	2	3	4	5	6	7
f_h^A	1	1	1	1	1	1	1
$\sum f_h^B$	0	0.6	0	0	0	0	0
f_h^C	0.1	0.1	0.1	0.1	0.5	0	0
f_h^D	0.2	0.2	0.2	0	0.2	0	0
α_i^P	0.19	0.28	0.19	0.16	0.25	0.14	0.14
C_1^p							**1.348**

TABLE 6. Calculation of liaison complexities - improved pressure recorder design.

	Liaison			
	1-3	1-5	2-3	2-5
f_f^E	2	1	2	2
f_f^F	4	4	1.3	1.3
f_f^G	0.1	0	0	0.1
f_f^H	0	0	0	0
f_f^I	0	0	0	1
f_f^J	0	0	0	0
f_f^K	0	0	0	0
β_{ij}^P	0.49	0.40	0.27	0.35
C_2^p				**1.516**

functional requirements. The results demonstrate that the proposed approach has accurately highlighted the effects of design improvements on assembly complexity in an explicit fashion.

B. THREE-PIN ELECTRIC POWER PLUGS

The second case is taken from [27], and is of the manual assembly of four three-pin power plugs (Figure 6) which are members of a product family. The variants consist of a number of similar components including the cord grip, fuse, fuse clip, pins, *etc*., and are handled by the same fixture as the four plug variants have identical base designs. The main difference between the variants is that the variants 1 and 2 use a direct screw to assemble the base and the cover components together, while the variants 3 and 4 use snap-fits to realise this connection. Moreover, the screw connecting the base

TABLE 7. **Calculation of product assembly complexities - All variants.**

	Component Complexity					Liaison Complexity					Overall Complexity			
α_i^p	1	2	3	4	β_{ij}^p	1	2	3	4		1	2	3	4
1	.19	.16	.19	.16	1-2	.55	.54	.19	.19	C_1^P	2.739	2.681	2.580	2.522
2	.19	.16	.19	.16	2-3	.46	.46	.46	.46	C_2^P	3.250	3.242	2.877	2.877
3	.19	.19	.19	.19	2-4	.46	.46	.46	.46	C_3^P	0.847	0.847	0.847	0.847
4	.19	.19	.19	.19	2-5	.46	.46	.46	.46					
5	.19	.19	.19	.19	2-6	.54	.54	.54	.54					
6	.19	.19	.19	.19	2-7	.60	.60	.60	.60					
7	.28	.28	.28	.28	7-8	.19	.19	.19	.19					
8	.22	.22	.22	.22										
9	.16	.16	.16	.16										
10	.16	.16	.16	.16										
11	.16	.16	.16	.16										
12	.16	.16	.16	.16										
13	.16	.16	.16	.16										
14	.16	.16	.16	.16										
15	.16	.16												
C_1^P	2.739	2.681	2.580	2.522	C_2^P	3.250	3.242	2.877	2.877	C^P	5.491	5.426	5.025	4.967

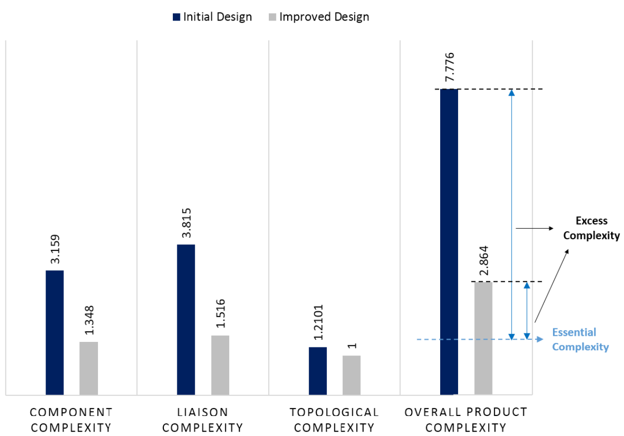

FIGURE 5. **Comparison between complexities of initial and improved pressure recorder designs. (Please note that, the value of essential complexity is arbitrarily selected.)**

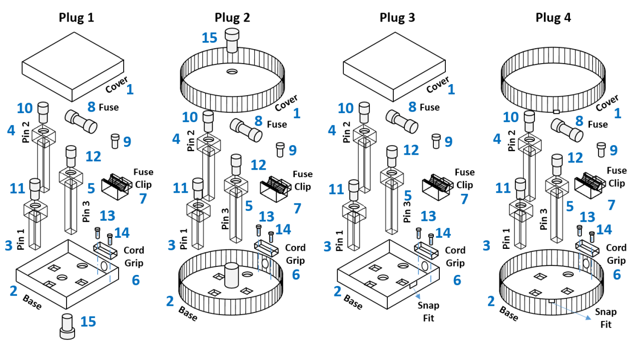

FIGURE 6. **Four variations of a three-pin power plug assembly (Product schematic is taken from [27].)**

and cover components is inserted from below in the first variant and from above in the second variant. In this section, assembly complexities of these variants are analysed to test the sensitivity of the proposed approach and the results are compared against the results found on the literature.

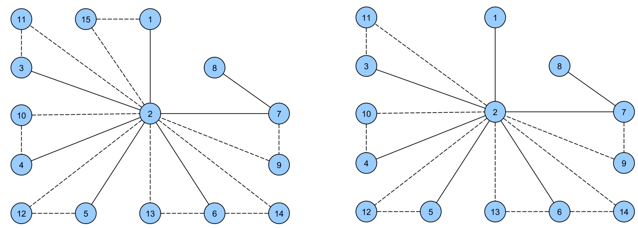

FIGURE 7. **Liaison diagram of the three-pin plug variants, *left*: Plugs one and two, *right*: Plugs three and four, $C_3^P = 0.847$.**

Topological complexity of the product is recorded as 0.847 for all variants (Figure 7). This value highlights that the product has a centralised architecture. All plugs are analysed, and overall product assembly complexities are calculated as shown in Table 7. According to the results, the plug variant one is found as the most complex design. Tables 8 and 9 show the component and liaisons complexity results of the plug variant one. Figure 8 illustrates the product complexity results for all variants. Even though the differences between complexity scores are very small, these differences are still traceable. The variant one has a higher cumulative component complexity (2.739) than the other three plugs, as its base and cover have more asymmetric shapes. On the other hand, the plug variants one and two require an additional screw to complete the liaison one, which slightly increases their cumulative component complexity scores. Moreover, it has been recorded that the variants one and two have higher cumulative liaison complexity scores than the variants three and four, as they use mechanical fastening method instead of snap-fits to achieve liaison one. This shows that the effects of changing structural attributes on the product assembly complexity are successfully tracked using the proposed approach.

The calculated complexity results are also compared with the estimations proposed by [27] for same product variants (Table 10). In their study, complexity of assembly

TABLE 8. Calculation of component complexities - Plug variant 1.

	Component														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
f_h^A	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
$\sum f_h^B$	0	0	0	0	0	0	0	0.4	0	0	0	0	0	0	0
f_h^C	0.1	0.1	0.1	0.1	0.1	0.1	0.5	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
f_h^D	0.2	0.2	0.2	0.2	0.2	0.2	0.4	0	0	0	0	0	0	0	0
α_i^P	0.19	0.19	0.19	0.19	0.19	0.19	0.28	0.22	0.16	0.16	0.16	0.16	0.16	0.16	0.16
C_1^p															**2.739**

TABLE 9. Calculation of liaison complexities - Plug variant 1.

	Liaison						
	1-2	2-3	2-4	2-5	2-6	2-7	7-8
f_f^E	2	1	1	1	2	2	1
f_f^F	4	4	4	4	4	4	1.3
f_f^G	0.1	0	0	0	0	0	0
f_f^H	0	0	0	0	0	0.7	0
f_f^I	0	0	0	0	0	0	0
f_f^J	0.7	0.7	0.7	0.7	0.7	0.7	0
f_f^K	0	0	0	0	0	0	0
β_{ij}^P	0.55	0.46	0.46	0.46	0.54	0.60	0.19
C_2^p							**3.250**

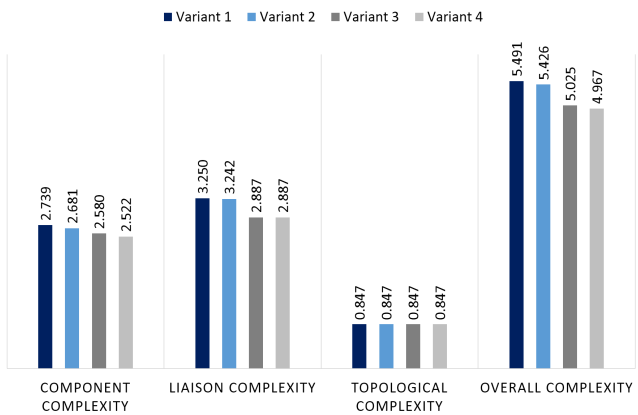

FIGURE 8. Product complexity result for all three-pin plug variants.

products is calculated using a heuristic methodology, in which the complexity is defined as a combination of quantity, diversity and the content of the information. According to the comparison, a similar trend has been observed in the estimations proposed by the presented study and [27]. Figure 9 shows the correlation between the calculated product assembly complexity and the approximate assembly times derived from the DFMA analysis (the data is taken from [27]). According to the results, a strong positive correlation is found between the product assembly complexity calculated by the proposed approach and assembly time of the variants derived from the DFMA (see [6]) ($R^2 = 0.9918$, a linear fit is used under a 95% confidence interval, Assembly Time (sec) $= -51.20305 + 16.321635$*Complexity). The results show that assembly time increases with an increase in the complexity.

TABLE 10. Comparison between product complexity and total assembly time.

	Products' assembly complexity		
Variant	Presented study	Samy and ElMaraghy [27]	Time (secs)
Plug 1	5.49	5.74	38.66
Plug 2	5.43	5.70	37.02
Plug 3	5.02	4.72	31.16
Plug 4	4.97	4.70	29.52

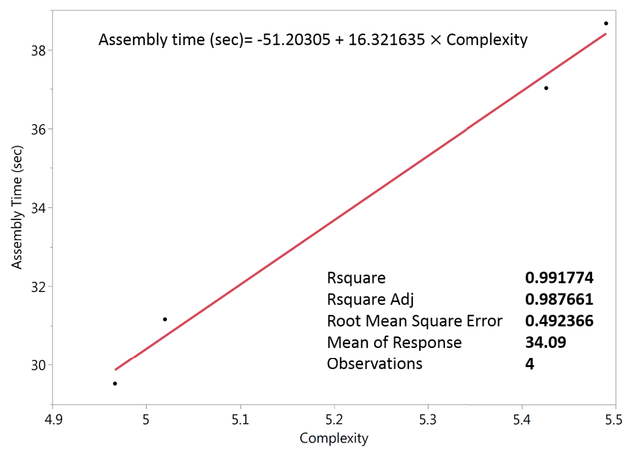

FIGURE 9. Correlation between manual assembly time and product complexity for three-pin power plug variants.

This is in consensus with the earlier hypothesis, and accordingly, the increased product complexity demands extra effort from the operators, thereby increasing the assembly time.

V. CONCLUSION

Complexity of manufacturing products manifests itself in various forms in different manufacturing systems. In a manual assembly system, complexity results in the increased difficulty/effort to perform assembly, eventually leading to defects and rework. On the other hand, automated assembly needs to be highly flexible to accommodate complex products. Therefore, it is important to define, measure and optimise the product's assembly complexity in early design stages, such that the time and effort needed in later stages of the product life cycle can be reduced. In this paper, a systemic approach to measure assembly complexity of manufacturing products has been proposed that allows the designer to track the root causes of complexity in the initial design stages.

Accordingly, the component and liaison complexities are measured along with the novel methodology to assess the topological complexity of the product architecture. Moreover, the approach is based on a scientifically validated empirical model and tested on two assembly cases from electronics industry. The results are in accordance with the proposed hypothesis and the variation in the product assembly complexity for the different cases, based on the product design is validated. The proposed approach solely depends upon physical design information and thus, can be considered as practical, especially for initial design stages, than the approaches requiring real production data. The approach can also be extended to include both process sequence and workspace related elements, such as: the type of part presentation, tool changes, *etc*., for optimising products' assembly sequences. Although, the approach in its current state is manually demanding, there is a huge opportunity to automate the calculations by integration with virtual engineering and design software to exploit the advantages of the approach. Virtual engineering tools are producing vast amounts of data (*e.g.* part and mating information, *etc*.) which, if streamlined and integrated, can be used as an input to the presented complexity model to realise concurrent design evaluation of industrial products during their virtual design phases. This, in turn, can reduce measurement efforts of the approach, and improve decision-making flexibility.

REFERENCES

[1] M. Ahmad *et al.*, "The use of a complexity model to facilitate in the selection of a fuel cell assembly sequence," *Proc. CIRP*, vol. 44, pp. 169–174, May 2016. [Online]. Available: http://www.sciencedirect.com/journal/procedia-cirp/vol/44/suppl/C

[2] B. Alkan, D. Vera, M. Ahmad, B. Ahmad, and R. Harrison, "Design evaluation of automated manufacturing processes based on complexity of control logic," *Proc. CIRP*, vol. 50, pp. 141–146, Aug. 2016. [Online]. Available: http://www.sciencedirect.com/journal/procedia-cirp/vol/50/suppl/C

[3] B. Alkan, D. Vera, M. Ahmad, B. Ahmad, and R. Harrison, "A lightweight approach for human factor assessment in virtual assembly designs: An evaluation model for postural risk and metabolic workload," *Proc. CIRP*, vol. 44, pp. 26–31, May 2016. [Online]. Available: http://www.sciencedirect.com/journal/procedia-cirp/vol/44/suppl/C

[4] S. S. Asan, "A methodology based on theory of constraints' thinking processes for managing complexity in the supply chain," Ph.D. dissertation, Fakultät V—Verkehrs- und Maschinensysteme, Technische Univ. Berlin, Berlin, Germany, 2009.

[5] S. N. S. Badrous, "Complexity of products and their assembly systems," Ph.D. dissertation, Dept. Ind. Manuf. Syst. Eng., Univ. Windsor, Windsor, ON, Canada, 2011.

[6] G. Boothroyd and L. Alting, "Design for assembly and disassembly," *CIRP Ann.-Manuf. Technol.*, vol. 41, no. 2, pp. 625–636, 1992.

[7] G. Boothroyd and P. Dewhurst, *Product Design for Assembly Handbook*. Wakefield RI, USA: Boothroyd Dewhurst, Inc, 1987.

[8] V. Chan and F. A. Salustri. *DFA: The Lucas Method*. Accessed: Sep. 29, 2017. http://deed.ryerson.ca/~fil/t/dfmlucas.html

[9] M. K. Chinnathai, B. Alkan, and R. Harrison, "Convertibility evaluation of automated assembly system designs for high variety production," *Proc. CIRP*, vol. 60, pp. 74–79, May 2017. http://www.sciencedirect.com/journal/procedia-cirp/vol/60/suppl/C

[10] S. Cho, R. Alamoudi, and S. Asfour, "Interaction-based complexity measure of manufacturing systems using information entropy," *Int. J. Comput. Integr. Manuf.*, vol. 22, no. 10, pp. 909–922, 2009.

[11] A. C. K. Choi, D. S. K. Chan, and A. M. F. Yuen, "Application of virtual assembly tools for improving product design," *Int. J. Adv. Manuf. Technol.*, vol. 19, no. 5, pp. 377–383, 2002.

[12] P. Dewhurst and N. Abbatiello, "Design for service," in *Design for X*. Dordrecht, The Netherlands: Springer, 1996, pp. 298–317, doi: https://doi.org/10.1007/978-94-011-3985-4

[13] W. ElMaraghy and R. Urbanic, "Assessment of manufacturing operational complexity," *CIRP Ann.-Manuf. Technol.*, vol. 53, no. 1, pp. 401–406, 2004.

[14] M. Gell-Mann, *The Quark and the Jaguar: Adventures in the Simple and the Complex*. New York, NY, USA: Freeman, 1994.

[15] C. M. Hinckley, "A global conformance quality model. A new strategic tool for minimizing defects caused by variation, error, and complexity," Ph.D. dissertation, Stanford Univ., Stanford, CA, USA, Jan. 1994.

[16] E. Hückel, "Quantentheoretische Beiträge zum Problem der aromatischen und ungesättigten Verbindungen. III," *Zeitschrift für Phys.*, vol. 76, nos. 9–10, pp. 628–648, 1932.

[17] W. Kinsner, "System complexity and its measures: How complex is complex," in *Advances in Cognitive Informatics and Cognitive Computing*. Springer, 2010, pp. 265–295.

[18] A. F. Lambert and S. M. Gupta, *Disassembly Modeling for Assembly, Maintenance, Reuse and Recycling*. Boca Raton, FL, USA: CRC Press, 2016.

[19] T. Lee, "Complexity theory in axiomatic design," Ph.D. dissertation, Dept. Mech. Eng., Massachusetts Inst. Technol., Cambridge, MA, USA, 2003.

[20] T. J. McCabe, "A complexity measure," *IEEE Trans. Softw. Eng.*, vol. SE-2, no. 4, pp. 308–320, Dec. 1976.

[21] S. Miyakawa and T. Ohashi, "The Hitachi assemblability evaluation method (AEM)," in *Proc. Int. Conf. Product Design Assembly*, Newport, RI, USA, Apr. 1986.

[22] V. Nikiforov, "The energy of graphs and matrices," *J. Math. Anal. Appl.*, vol. 326, no. 2, pp. 1472–1475, 2007.

[23] S. Y. Nof, W. Wilhelm, and H. Warnecke, *Industrial Assembly*. Springer, 2012.

[24] E. Rechtin, *Systems Architecting: Creating and Building Complex Systems*. Englewood Cliffs, NJ, USA: Prentice-Hall, 1991.

[25] M. Richardson, G. Jones, M. Torrance, and T. T. Baguley, "Identifying the task variables that predict object assembly difficulty," *Human Factors, J. Human Factors Ergonom. Soc.*, vol. 48, no. 3, pp. 511–525, 2006.

[26] S. N. Samy and H. ElMaraghy, "A model for measuring complexity of automated and hybrid assembly systems," *Int. J. Adv. Manuf. Technol.*, vol. 62, pp. 813–833, Sep. 2012.

[27] S. Samy and H. ElMaraghy, "A model for measuring products assembly complexity," *Int. J. Comput. Integr. Manuf.*, vol. 23, no. 11, pp. 1015–1027, 2010.

[28] H. Shibata, B. Cheldelin, and K. Ishii, "Assembly quality methodology: A new method for evaluating assembly complexity in globally distributed manufacturing," *Des. Eng.*, vol. 1, no. 2, pp. 335–344, 2003.

[29] K. Sinha, "Structural complexity and its implications for design of cyber-physical systems," Ph.D. dissertation, Eng. Syst. Div., Massachusetts Inst. Technol., Cambridge, MA, USA, 2014.

[30] K. Sinha and O. L. D. Weck, "Structural complexity metric for engineered complex systems and its application," in *Proc. 14th Int. DSM Conf. Gain Competitive Advantage by Manag. Complexity* Kyoto, Japan, 2012, pp. 181–194.

[31] K. Sinha and O. L. de Weck, "Structural complexity quantification for engineered complex systems and implications on system architecture and design," in *Proc. Int. Design Eng. Tech. Conf. (IDETC)*, vol. 3A. Portland, OR, USA, Aug. 2013. [Online]. Available: http://proceedings.asmedigitalcollection.asme.org/proceeding.aspx?articleid=1830329

[32] K. Sinha, N. R. Shougarian, and O. L. D. Weck, "Complexity management for engineered systems using system value definition," in *Complex Systems Design & Management*. Paris, France: Springer, 2017, pp. 155–170. [Online]. Available: http://www.springer.com/gb/book/9783319491028

[33] Q. Su, L. Liu, and D. E. Whitney, "A systematic study of the prediction model for operator-induced assembly defects based on assembly complexity factors," *IEEE Trans. Syst., Man, Cybern. A, Syst., Humans*, vol. 40, no. 1, pp. 107–120, Jan. 2010.

[34] S. Vongbunyong and W. H. Chen, "General disassembly process," in *Disassembly Automation: Automated Systems With Cognitive Abilities*. Cham, Switzerland: Springer, 2015, pp. 9–24. [Online]. Available: http://www.springer.com/gb/book/9783319151823

BUGRA ALKAN received the M.Sc. degree in mechanical engineering from the Izmir Institute of Technology, Izmir, Turkey, in 2012. He is currently pursuing the Ph.D. degree in manufacturing engineering with the Warwick Manufacturing Group, University of Warwick, U.K. His main research interests include statistical experimental design, design for manufacturing and assembly, performance optimization in production systems, assembly process planning, industrial ergonomics, and robotics.

DANIEL VERA received the M.Sc. degree in mechanical and manufacturing engineering from École nationale d'ingénieurs de Tarbes, Tarbes, France, in 2000, and the Ph.D. degree in manufacturing engineering from Loughborough University, Loughborough, U.K., in 2004. His research interests are focused on various aspects of manufacturing from the modeling, analysis, and optimization of engineering processes to the design and development of 3-D-based virtual engineering and collaboration tools for supporting the manufacturing system lifecycle.

BILAL AHMAD (M'15) received the M.Sc. degree in mechatronics and the Ph.D. degree in automation systems from Loughborough University, Loughborough, U.K., in 2007 and 2014, respectively. He is currently a Senior Research Fellow with the Warwick Manufacturing Group, University of Warwick, Coventry, U.K. His research interests are in the area of virtual modeling and control software engineering of industrial automation systems.

ROBERT HARRISON received the B.Tech. and Ph.D. degrees in mechanical and manufacturing engineering from Loughborough University, Loughborough, U.K., in 1981 and 1991, respectively. He is currently a Professor of automation systems with the Warwick Manufacturing Group, University of Warwick, U.K. He was a recipient of the Royal Academy of Engineering Global Research Award to study Life-cycle Engineering of Modular Reconfigurable Manufacturing Automation.